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Techniques for Improving the Accuracy of Cryogenic Temperature Measurement in Ground Test Programs

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TECHNIQUES FOR IMPROVING THE ACCURACY OF CRYOGENIC TEMPERATURE MEASUREMENT IN GROUND TEST PROGRAMS

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ABSTRACT

The performance of a sensor is often evaluated by determining to what degree of accuracy a measurement can be made using this sensor. The absolute accuracy of a sensor is an important parameter to be considered when choosing the type of sensor to use in research experiments. Tests were performed to improve the accuracy of cryogenic temperature measurements by calibration of the temperature sensors when installed in their experimental operating environment. The calibration information was then used to correct for temperature sensor measurement errors by adjusting the data acquisition system software. This paper describes a method to improve the accuracy of cryogenic temperature measurements using corrections in the data acquisition system software such that the uncertainty of an individual temperature sensor is improved from $\pm 0.90\ ^{\circ}R$ (degrees Rankine) to $\pm 0.20\ ^{\circ}R$ over a specified range.

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INTRODUCTION

Future space programs will require the development of long term storage methods and efficient fluid transfer and supply techniques of cryogens. The goal of the Cryogenic Fluids Systems Branch (CFSB), of the Space Propulsion Technology Division, at NASA Lewis Research Center, is to develop the technology to enable the design of cryogenic fluid management systems in space.

Several ground test programs are underway within this office to demonstrate cryogenic fluid management techniques. Liquid storage (1,2), liquid supply (pressurization),and liquid transfer (no-vent fill) (3) experiments are performed in ground test facilities to provide a better understanding and to verify analytical models of the physical processes using liquid hydrogen as the cryogenic fluid. For example, the data from one of the experiments will be used to verify or improve existing models for the prediction of thermal stratification in cryogenic tanks (1). In order to predict the growth of the stratified layer, a large number of temperature measurements within $\pm 0.20\ ^{\circ}R$ accuracy, at 36 °R, are required. The researchers also require the maximum number of sensors the facility can handle. Installing the maximum number of sensors with the minimum number of wires and connectors is a challenge to all instrumentation engineers. In addition, there are a limited number of commercially available connectors for use in a cryogenic environment.

Although there are numerous sensors available for measuring temperature, there are many constraints limiting the choice based on the application. Past experience with thermocouples, platinum resistance thermometers, thermistors, and silicon diodes has shown that silicon diodes are the most cost effective method to measure cryogenic temperature in this application. However, the standard manufacturing accuracy of silicon diodes is only within $\pm$ 0.90 °R.

This paper will also discuss techniques for improving the accuracy of cryogenic temperature measurement using a software calibration procedure, good design practices, and installation techniques, which result in an improved accuracy of $\pm$0.20 °R.

ANALYSIS

The silicon diodes used for this experiment were designed to follow a standard temperature response curve. This standard curve is shown in figure 1-1. The sensors were specified by the manufacturer to be within $\pm 0.90\ ^{\circ}R$ of this standard curve. Calibrated sensors with accuracies within $\pm 0.20\ ^{\circ}R$ are available from the manufacturer, but cost three times as much as standard sensors, and require a four wire configuration to obtain this accuracy. These were not used due to cost and other system constraints such as facility wiring available, heat leak into the test article, and the number of tank feedthrough connectors. The procedure described in this paper saves the cost associated with purchasing individually calibrated sensors.

Millivolt output for the temperature sensors was converted to engineering units in the data acquisition software by a Chebychev curve fit subroutine supplied by the manufacturer. This subroutine is accurate to within $\pm 0.002\ ^{\circ}R$. The resolution of the data system is ± 0.078 mV (millivolts) at the operating range of the silicon diodes. This is the temperature equivalent of $\pm 0.007\ ^{\circ}R$. The data system used has a higher resolution than the required accuracy of the measurement.

In addition to the manufacturer specified accuracy band $\pm 0.90\ ^{\circ}R$, several secondary errors were present in the system (4). The total temperature measurement uncertainty may be defined as

$$(T)^2 = \sum_{i=1}^{7} (T_i)^2 \tag{1-1}$$

where

T_1 error due to the current source = ±0.009 °R
T_2 data system voltage measurement effect = ±0.092 °R
T_3 error due to deviation from typical response curve (mfg. specs.)= ±0.900 °R
T_4 error due to engineering unit conversion subroutine = ±0.002 °R
T_5 measurement error due to ac noise = negligible (minimized by using twisted pairs)
T_6 self heating error = negligible (due to mounting and design)
T_7 lead effect = 0.047 °R (only effect from lid to sensor, see figure 1-3.

Combining the above gives

$$T = \pm 0.905\ ^{\circ}R.$$

The required accuracy was ± 0.20 °R for temperature measurements in liquid hydrogen. As can be seen by the above calculation, this uncertainty was not acceptable for the scheduled tests. For this reason a method of calibrating these diodes in liquid hydrogen to increase the measurement accuracy was devised. The calibration method was based on the results of boil-off and self-pressurization tests performed in ground tests facilities (1,2). Initially a tank is filled with LH_2 to 95 percent of capacity to chill the tank to within ±1.0 °R of the saturation temperature at the tank vent pressure. Boil-off rate is monitored until steady state conditions are obtained for boil-off, fluid, wall, and insulation temperatures. The tank pressure is then reduced to the back pressure level, causing bulk boiling of the fluid. Temperature and boil-off flowrates are monitored until steady state conditions are once again achieved in the test tank. When the change in these two parameters is within the error band of their specifications, the bulk liquid is at saturation conditions. If stratification was present in the test tank, the boil-off would not stabilize.

Using this information, a method was developed to calibrate the test tank temperature sensors based on tank pressure at saturation conditions. Instead of using an expensive temperature sensor to calibrate temperature sensors in the tank, a pressure transducer could be used.

The error effect on temperature caused by this 0 to 50 psia pressure transducer was checked. The total pressure measurement uncertainty is defined as

$$(P)^2 = \sum_{i=1}^{7} (P_i)^2 \tag{1-2}$$

where

P_1 error due to linearity offset in the calibration = ±0.010 psia
P_2 error due to calibration of the transducer with the barometer = ±0.016 psia
P_3 data system error = ±0.035 psia

P_4 nonrepeatability error = ± 0.050 psia

P_5 RCal error = ± 0.100 psia

P_6 thermal shift error = 0.100 psia (this error can be eliminated by holding the temperature of the transducer at 540 °R)

P_7 pressure head error due to level of liquid above sensor (worst case) = ± 0.151 psia.

Combining these gives

$$P = \pm 0.216 \text{ psia.}$$

Per the thermodynamic tables for LH_2, the temperature change due to a change in pressure measurement is equal to

$$\frac{dT}{dP} \times P \tag{1-3}$$

The operating range of the LH_2 tank is 15 to 45 psia. At 15 psia, temperature error due to pressure transducer error equals ± 0.086 °R., i.e.,

$$[\pm 0.216\text{psia x } (Tsat_{@15psia} - Tsat_{@14.784psia})/(15\text{psia} - 14.784\text{psia})].$$

Similarly, at 45 psia, temperature error due to transducer error equals ± 0.043 °R. The accuracy of the saturation temperature calculation is specified to be within ± 0.02 percent of the temperature (6). This error has an effect of less than ± 0.016 °R on temperature. Replacing the error in equation (1-1) due to the deviation from the typical response curve (T_s)with the errors due to the calibration procedure, ± 0.086 °R and ± 0.016 °R, the total measurement uncertainty is equal to ± 0.135 °R. This is within the ± 0.20 °R accuracy requirement.

EXPERIMENTAL APPARATUS

Hardware

The tests on the silicon diodes were performed in support of a NASA Lewis cryogenic fluid management test program. Tests were performed in a 175 ft^3 (cubic feet) ellipsoidal LH_2 (liquid hydrogen) tank, surrounded by a 13-ft cylindrical cryoshroud, and contained in a 25-ft spherical vacuum chamber. This test facility is located at NASA Plum Brook Station in Sandusky, Ohio. The 175 ft^3 LH_2 tank is shown in figure 1-2. This test facility was used for the cryogenic experiments described in references 1,2, and 3. Previous tests had shown that thermocouples lacked accuracy, while platinum sensors were costly and time consuming to set-up.

Test tank pressure was controlled by a closed loop system capable of maintaining tank pressure within ± 0.02 psia. The system consisted of a hydraulic valve, controller, and a strain gage pressure transducer controlled to a constant temperature.

Instrumentation

Silicon diodes were chosen as the temperature measuring devices because of their high sensitivity, stability, wide temperature range, simplicity, and relatively low cost. Silicon diodes were mounted on an instrumentation rake as detailed in figures 1-3 and 1-4. The silicon diodes were wired in series as shown in figure 1-5, minimizing the number of wires. Minimizing the number of wires minimized the solid conduction heat input into the test tank due to the leads. This rake along with a capacitance liquid level probe were mounted to the lid of the 175-ft^3 tank. A strain gage pressure transducer was used to measure tank pressure. This pressure transducer was located outside the vacuum chamber in a temperature controlled dewar maintained at 540 °R.

Data Acquisition

A NASA Lewis designed data acquisition system identified as ESCORT D was used during the test program (5). The ESCORT D configuration consisted of a facility-located MicroVAX that performed all real time functions including: acquisition, display functions, recording, transmission, engineering unit conversions, and calculations. These data channels were transmitted from NASA Plum Brook Station to a VAX Cluster located 50 miles away at NASA Lewis in Cleveland, Ohio. The data channels were then stored on the VAX Cluster for post run data processing. The scan rate was once every second for all the data channels.

PROCEDURE

The procedure consisted of first dipping the sensors in LN_2 (liquid nitrogen) at atmospheric pressure, 140 °R to verify they were within the performance criteria stated by the manufacturers specifications at LN_2 temperatures. The sensors were then installed on the instrumentation rake and the rake suspended into the 175 ft^3 test tank. Then, LH_2 was added to the tank until all the sensors were immersed. Saturation conditions were created in the tank by the following test procedure:

1. The test tank vent pressure was set at 4 psia above the operating pressure (17 psia) of the back pressure control system.

2. The test tank was filled to 92 percent liquid level. Verification was obtained that all the silicon diodes were immersed in liquid by the level measured by the capacitance liquid level probe, and observing tank temperatures.

3. After the tank temperatures stabilized, the test tank vent pressure was slowly decreased to the operating pressure (17 psia) of the back pressure control system. Saturation temperatures of LH_2 at 17 psia equals 37.4 °R.

4. Silicon diode temperatures and the boil-off rate of the GH_2 (gaseous hydrogen) were monitored. Temperatures were plotted versus time. When the change in temperature over change in time

(dT/dt) approached zero, and the boil-off rate stabilized, within the error band of the measuring system, the bulk liquid in the tank was at saturation conditions.

5. A strain gage pressure transducer was used to measure tank saturation pressure. This pressure was the reference used to determine corresponding saturation temperature.

Software Calibration Procedure

The silicon diode temperature readings were offset in the ESCORT D data acquisition system software so that all diodes immersed in the liquid were referenced to the saturation temperature. A command was executed that began an averaging of the silicon diodes for 10 scans. The scan rate was once every second. An example of the procedure is described for 1 of the 28 sensors:

1. Using SD36, calculate the average of these 10 scans.

2. Calculate the saturation temperature, TSAT, with an LH_2 property subroutine based on tank pressure (6). The property subroutine is based on NIST (National Institute of Standards and Technology) tables.

3. Calculate the offset of SD36,

where

$$\text{offset(SD36)} = \text{TSAT} - \text{average (SD36)} \tag{1-4}$$

4. Add the offset to the SD36 temperature measurement for all future readings. This procedure was repeated simultaneously for all 28 silicon diodes. These offset values were stored.

After the software calibrations were performed, the calibration of the silicon diodes was checked at 29 psia (41.03 °R saturation temperature). This was done by bubbling warm gas through the liquid hydrogen, and controlling tank pressure. Silicon diodes temperatures and the GH_2 boil-off rate were monitored. Temperatures were plotted versus time. When the change in temperature over change in time (dT/dt) approached zero, and the boil-off rate stabilized, the bulk liquid in the tank was again at saturation conditions.

RESULTS

The results from this test are plotted on figures 1-7 to 1-13. Figure 1-7 is a plot of temperature versus time in the bulk liquid prior to calibration. Saturation conditions were achieved after 7 hours. Figures 1-8 to 1-11 plot the temperature measured prior to the software change, and then after the correction was made 10.13 hours into the test. Saturation temperature was also plotted on these figures. Tank pressure was 17 psia. As can be observed from the data, many of the temperature sensors were not within ± 0.20 °R of saturation temperature prior to application of the offset.

This software calibration was then checked at 29 psia. Figure 1-12 plots the temperature as saturation conditions in the bulk liquid were again established. Figure 1-13 plots the calibrated temperatures of the sensors and the saturation temperature at this new pressure. The correction seems to hold for this higher pressure range since the temperatures were still within $\pm 0.20\ ^{\circ}R$ of saturation temperature.

DISCUSSION

Many of the errors mentioned in the previous section were negligible due to good design and installation practices. Temperature measurement at cryogenic temperatures can be affected by the transfer of heat into the system by conduction down the solid lead wires. The physical processes analyzed during the ground test program were very sensitive to these types of heat leaks. If heat flow down the leads by conduction was not minimized, the experimental data recorded during the process would be affected. One good design practice included keeping the number of wires to a minimum. This decreased the number of possible conduction paths, and the number of connectors. Thin manganin wire was a good choice for minimizing conduction in the leads. In addition, the connectors that can be used in a cryogenic environment are expensive, and the use of several connectors increases design problems.

One technique used to minimize the number of wires was to wire nine diodes in series on one power supply. The number of diodes was limited to nine because the constant current source has a 12-V compliance, and the voltage drop across each diode at cryogenic temperatures is equal to 1.280 V. By wiring these diodes in series (figure 1-5), only 12 wires were used for every 9 sensors. An RTD, in comparison, would need four wires and special signal conditioning for each individual sensor for the same accuracy requirement. A thermocouple would only need two wires, but is not as accurate at cryogenic temperatures. Only 1 lead wire is used for each of the middle 7 sensors. By wiring in series, and by measuring the voltage drop from lead to lead instead of from each individual lead to ground, the advantages of a 4 lead arrangement are still utilized. The four lead configuration is good engineering practice, and important in cryogenics because this configuration allows the use of high resistance leads which minimizes heat flow. The four wire system provides separate leads for measurement and separate leads for the current source. By supplying the current source through one pair of leads, and measuring the voltage across pairs of leads, the current is not carried on the measuring leads, eliminating the voltage drop down the leads present in the two lead configuration.

Another technique used to increase the accuracy of the measurement is to verify the sensor is measuring the correct parameter. For example, inside the tank, the sensor should be mounted so that it measures liquid or gas temperature only, not the temperature of the mounting fixture. These sensors were mounted by the leads as shown in figure 1-6. To measure a surface temperature, like the tank wall, a thin film adhesive that supplies the maximum thermal transfer between the sensor and the surface would be required. The sensor should also be insulated from external temperatures. This can be achieved by covering the sensor with mylar tape. In addition to this, the leads should be run along isotherms to minimize heat conduction errors due to temperature gradients in the leads.

CONCLUDING REMARKS

The software calibration of silicon diodes is a feasible method of achieving highly accurate cryogenic temperature measurements within a reasonable cost in situations where several diodes can be brought to saturation conditions. Good design and installation practices are also important in achieving accurate temperature measurements. Future tests will be performed to determine whether this method can be used for a larger pressure range.

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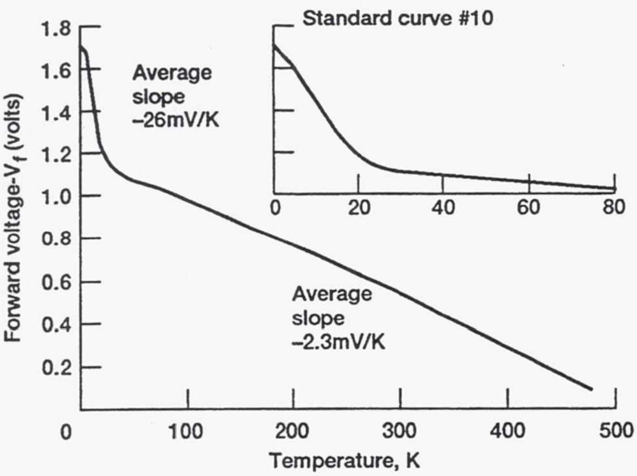

Figure 1.1.—Manufacturer supplied standard standard temperature response curve reprinted with written permission of Lake Shore Cryotronics, Inc.

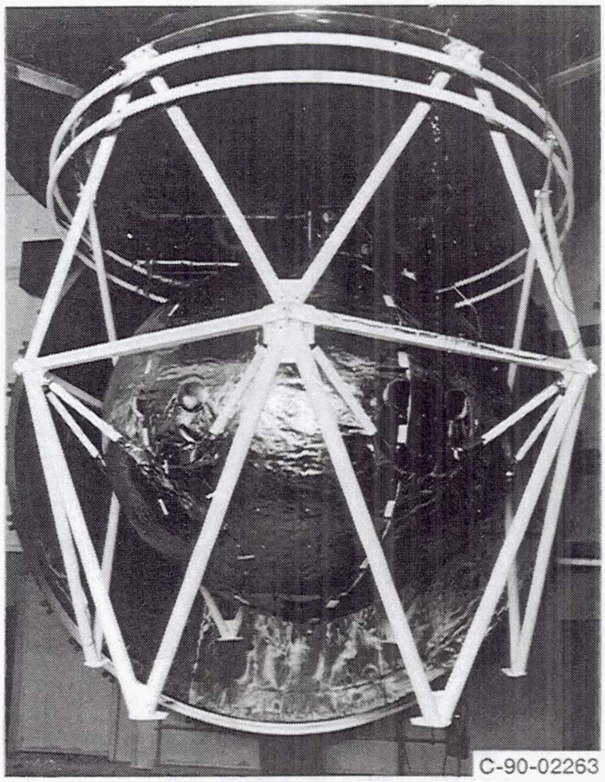

Figure 1.2.—175 ft^3 LH^2 test tank.

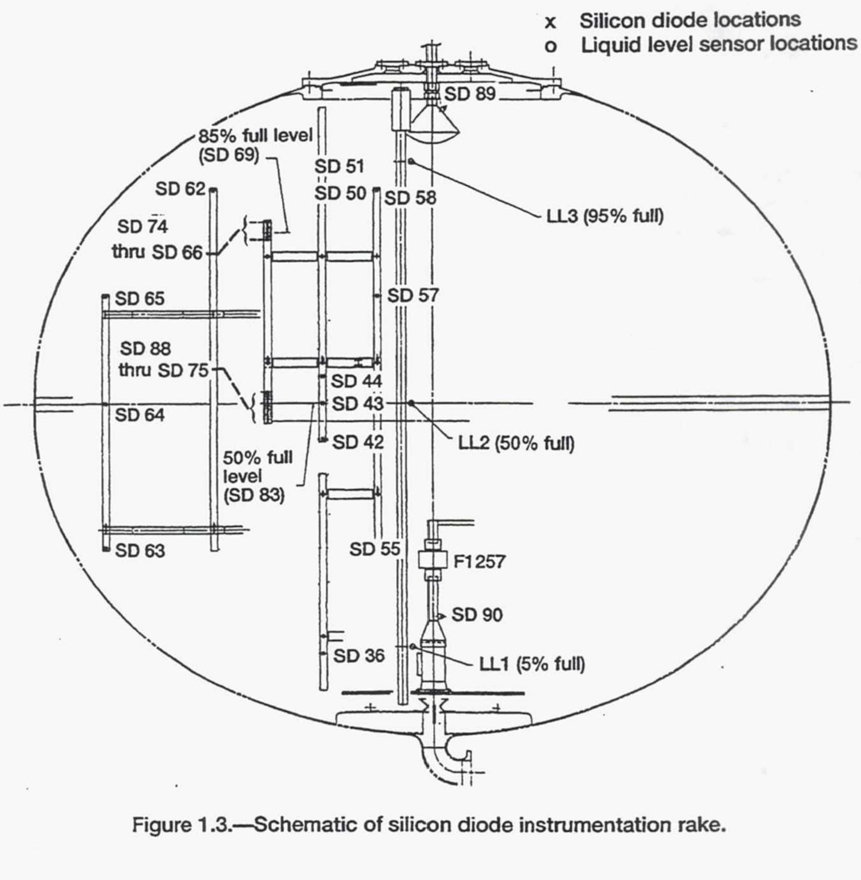

Figure 1.3.—Schematic of silicon diode instrumentation rake.

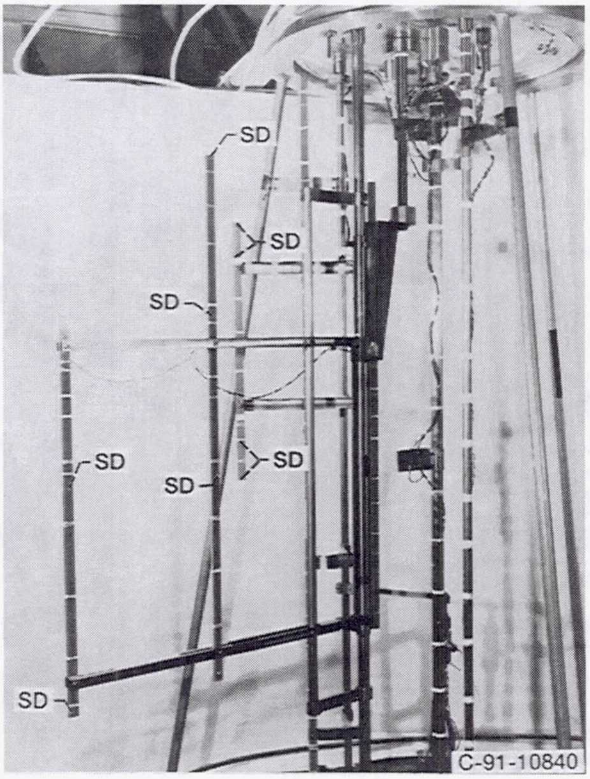

Figure 1.4.—Photograph of silicon diode instrumentation rake

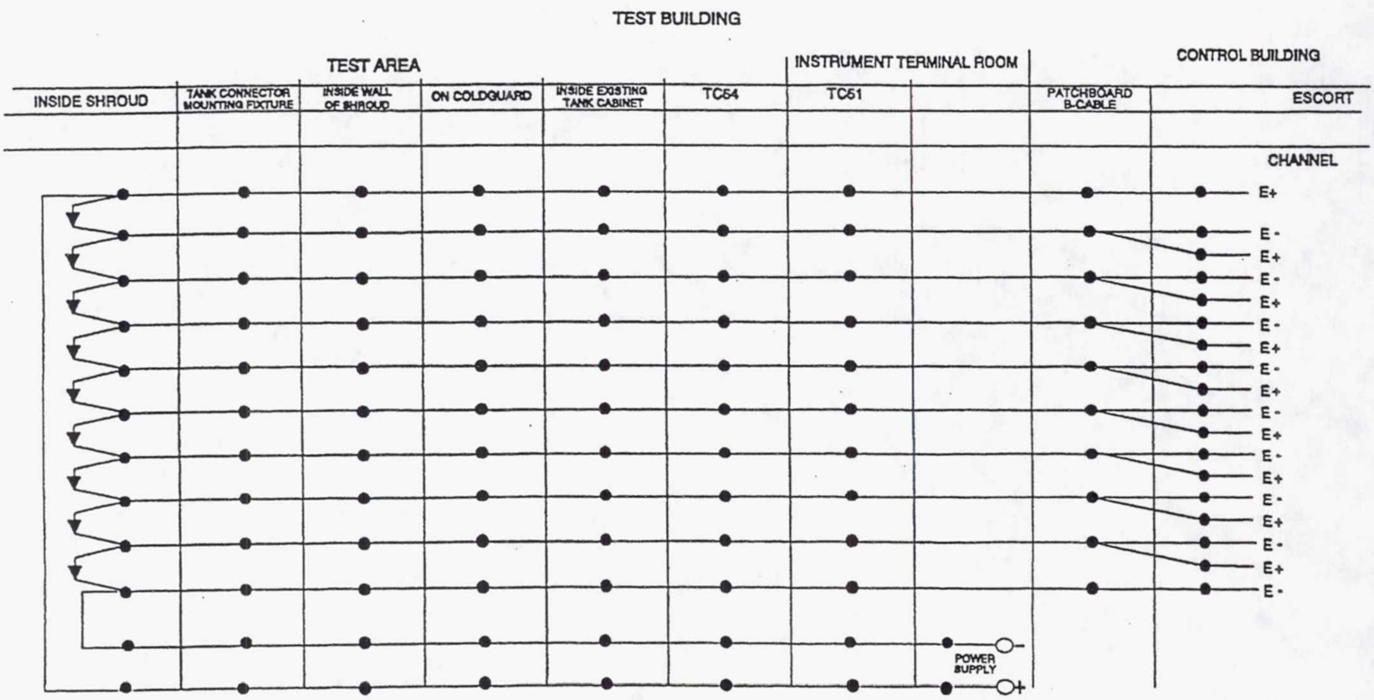

Figure 1.5.—Silicon diode wiring diagram.

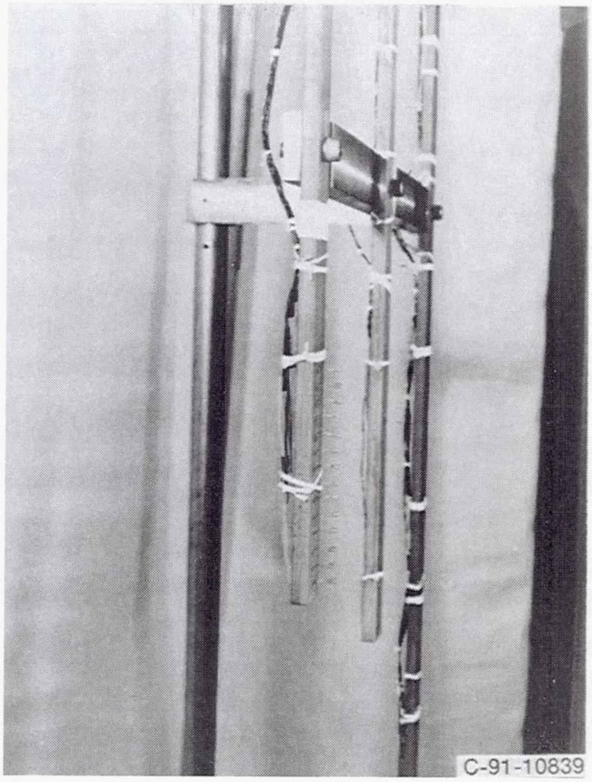

Figure 1.6.—Photograph of silicon diode mounting.

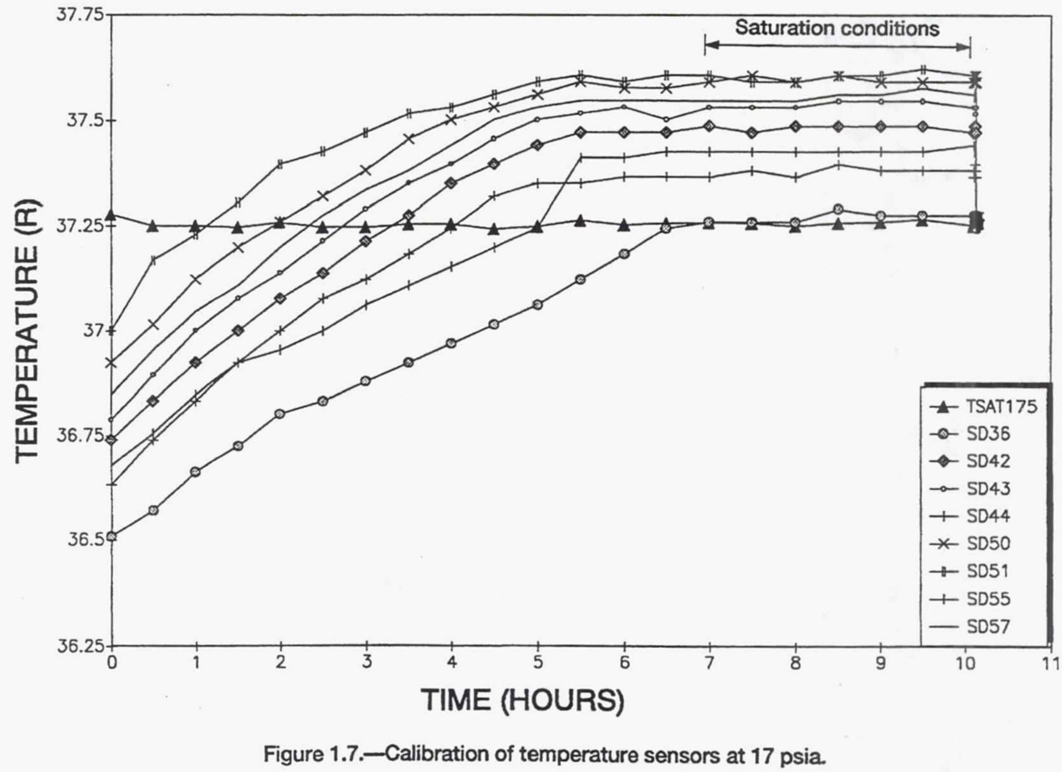

Figure 1.7.—Calibration of temperature sensors at 17 psia.

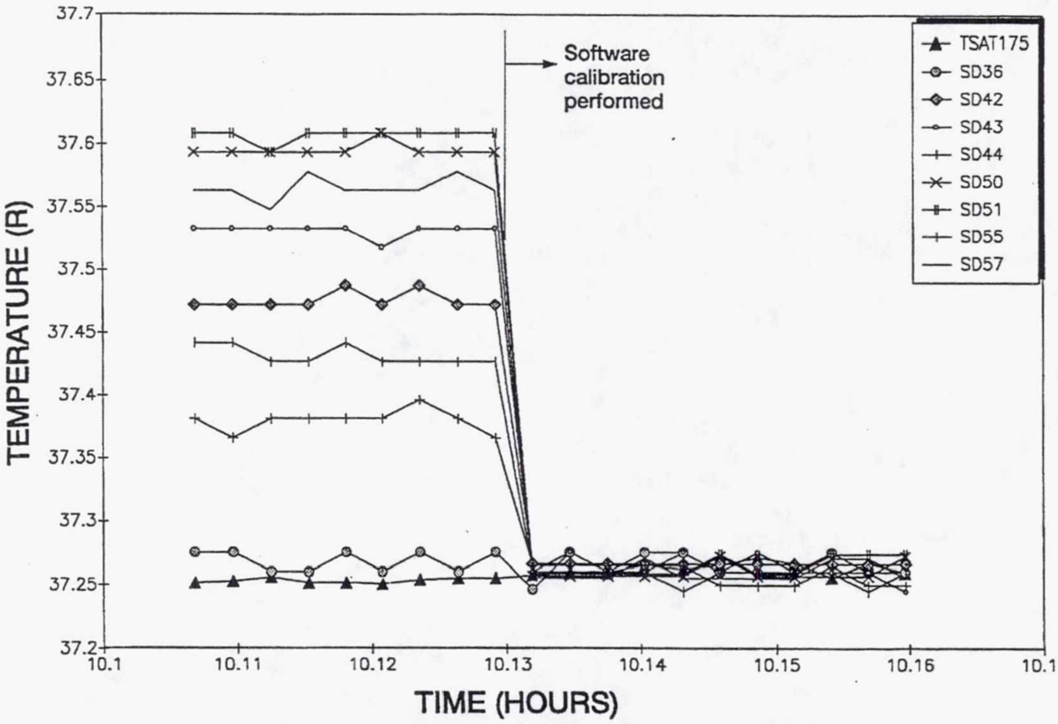

Figure 1.8.—Calibration of temperature sensors at 17 psia.

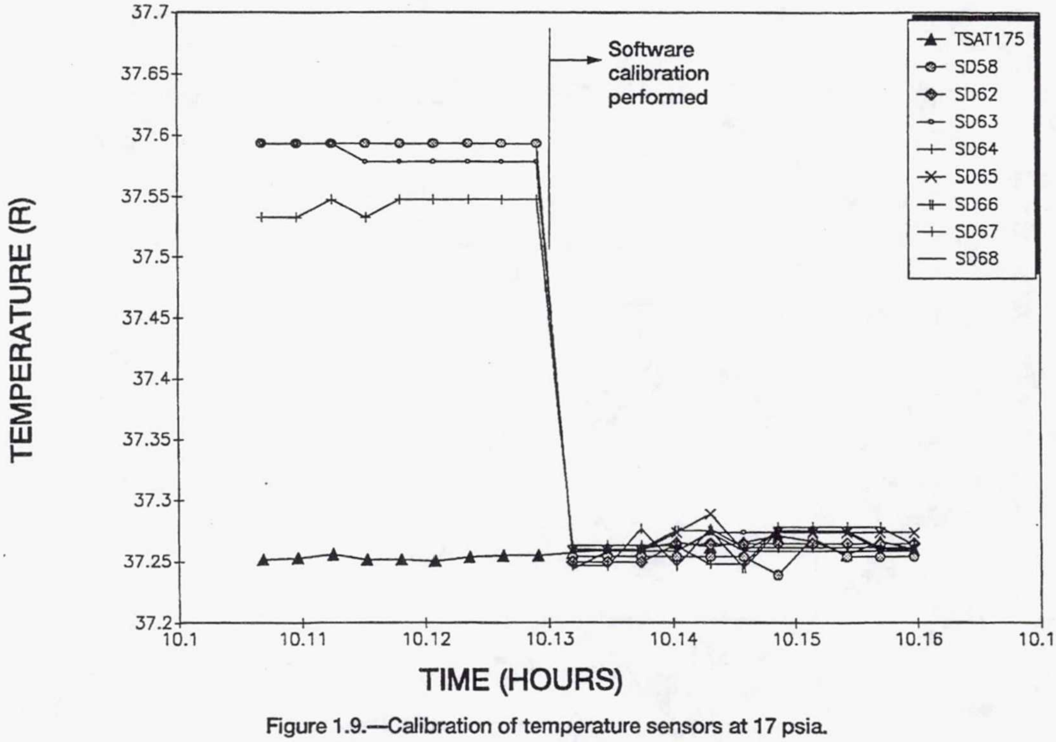

Figure 1.9.—Calibration of temperature sensors at 17 psia.

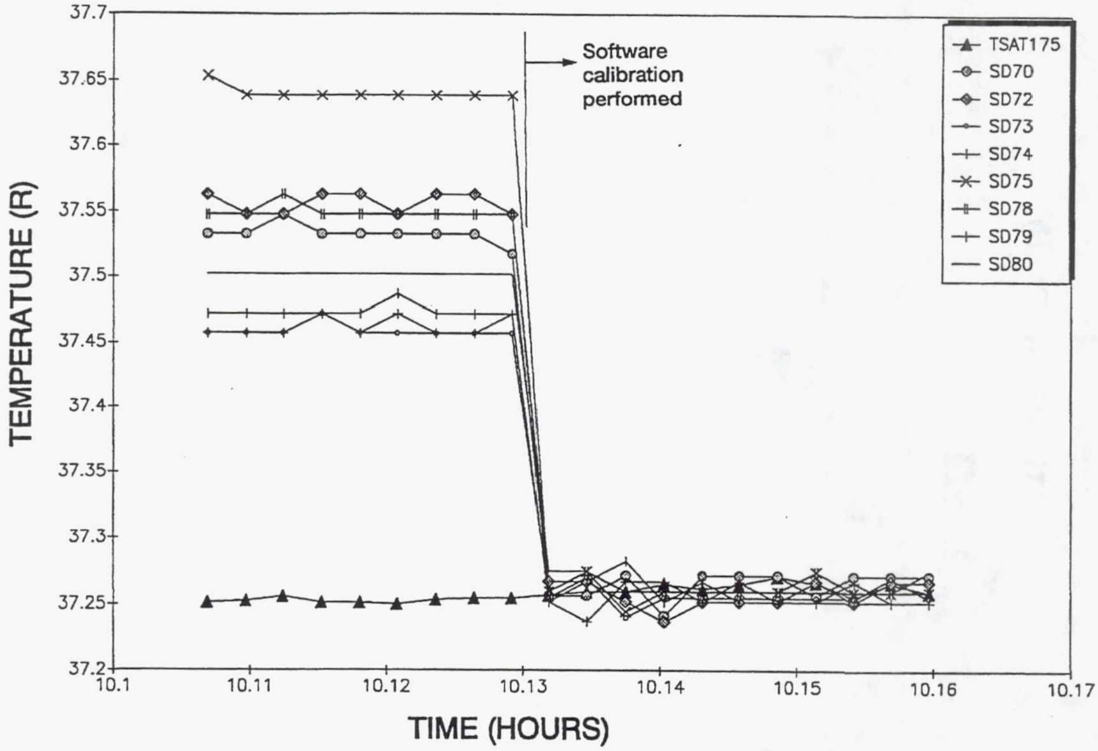

Figure 1.10.—Calibration of temperature sensors at 17 psia.

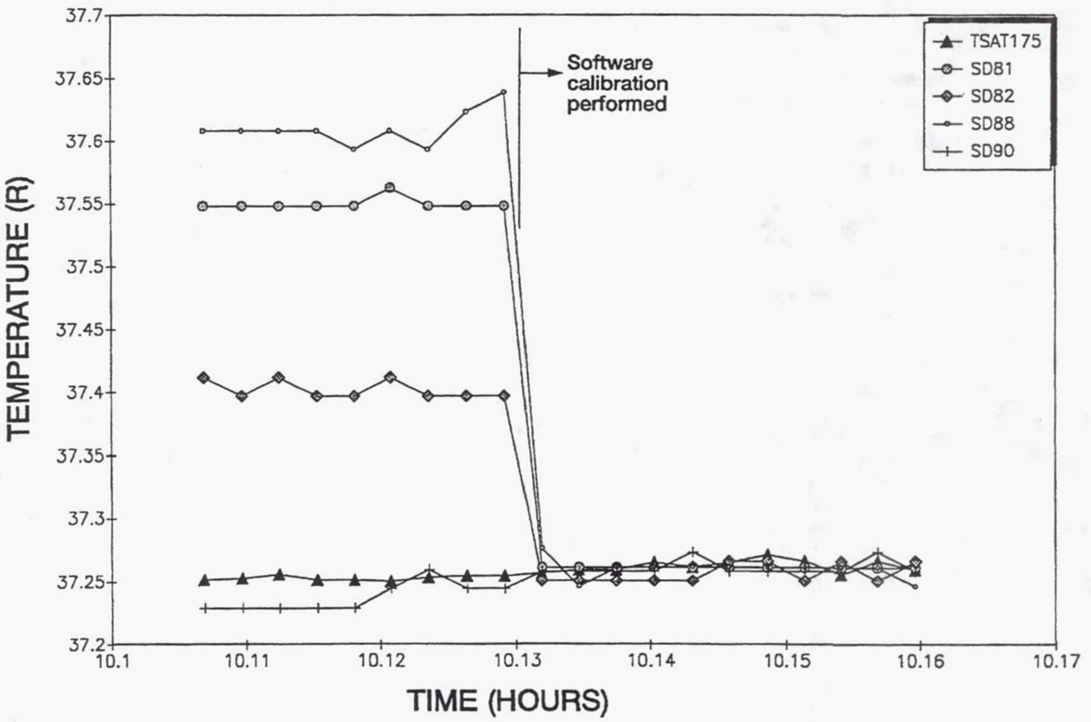

Figure 1.11.—Calibration of temperature sensors at 17 psia.

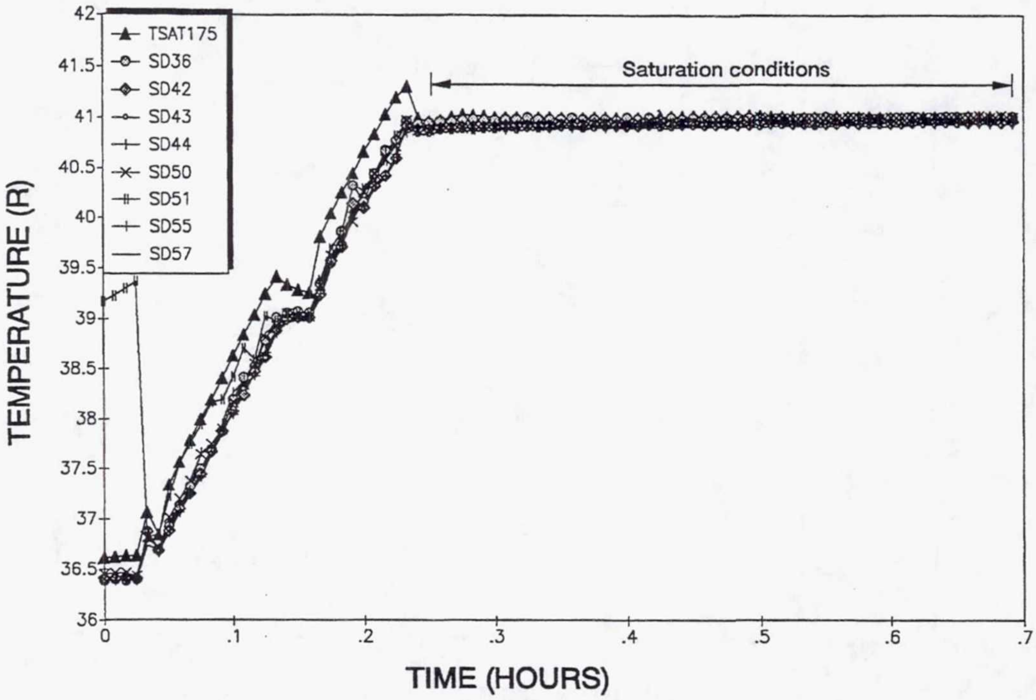

Figure 1.12.—Calibration of temperature sensors at 29 psia.

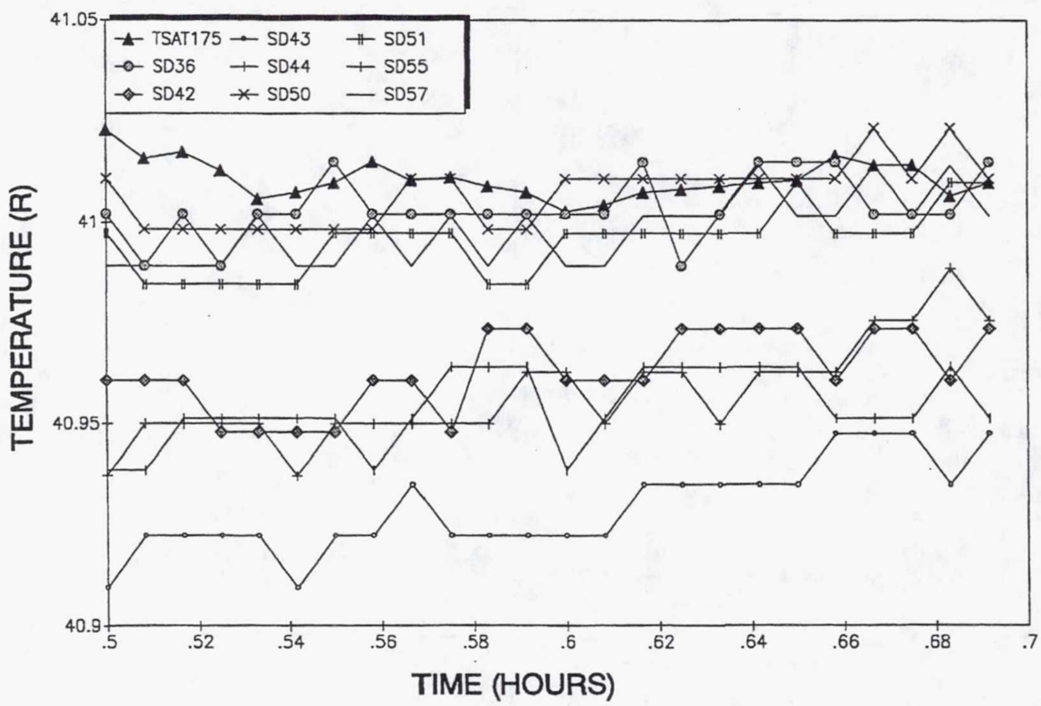

Figure 1.13.—Calibration of temperature sensors at 29 psia.

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13. ABSTRACT ***(Maximum 200 words)***

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